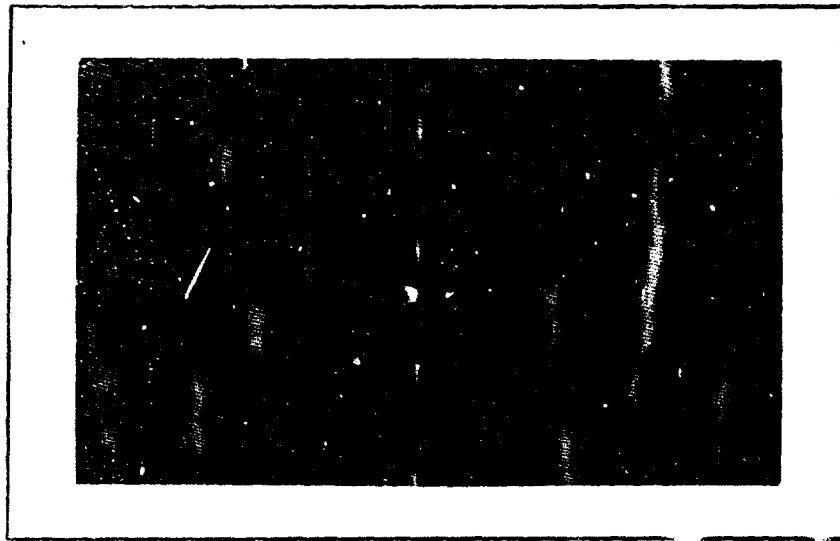


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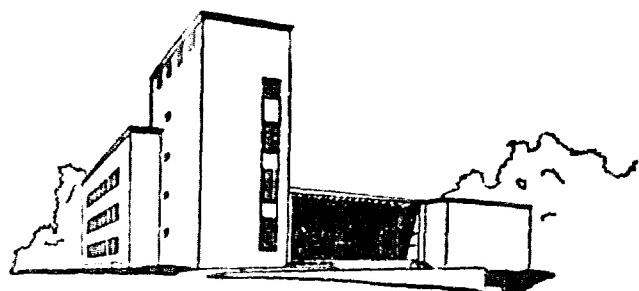


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Management Sciences Research Report No. 115

A GOAL PROGRAMMING MODEL  
FOR  
MANPOWER PLANNING  
BY

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## 1. Introduction

This report should be regarded as the first in a series of technical reports directed toward the erection of manpower planning and control models for the Office of Civilian Manpower Management (OCMM) in the U. S. Navy. It should also be borne in mind that this is only one part of a three-pronged program that involves: (i) Preparation of a conceptual paper which will provide (a) a statement of the manpower-management problem at OCMM and (b) a statement of objectives, as well as (ii) Development of a systems blueprint which will tie the elements of the problem together with the information requirements and decision possibilities and (iii) Provision for a continuing research effort pointed toward a synthesis of suitable models for implementing the latter (i.e., system) results in the light of the stated problems and objectives.<sup>1</sup>

It was recognized that there need not be any delay in carrying out any part of this program pending completion of the other portions. Provided contact and coordination could be maintained between the persons who were involved, something might be gained, in fact, by utilizing developments in each phase so that they could interact with and clarify issues in the other two phases.

This, then, is an objective of the present report. More precisely, we propose to introduce a series of technical (mathematical) developments which will help to clarify some of the possibilities that are now present.

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<sup>1</sup>Summarized from [34.1.a].

This should be regarded, however, as only a beginning for such possibilities.

It does not represent a final commitment.

In addition to the opportunity that this presents for exploring the possibilities for modelling, we have tried to present this report so that it will help to clarify issues for the proposed systems blueprint as well. For instance, we have provided a numerical illustration in order to help focus on issues like data availability, forecasting and estimation requirements, etc. We have not undertaken the further mathematical research that would be needed for the development of solution procedures, or even more compact (and elegant) representations.<sup>1</sup> As of the moment, it seems better to focus on other issues which are best served, we believe, by restricting attention to modelling possibilities and systems synthesis at OCMM.

Although the numerical illustration is grossly oversimplified, we should probably also make clear that the proposed model already differs in some respects from others which are now available. To be sure, it incorporates Markovian elements, as do many other models, but these are only part of a total model of goal-programming variety<sup>2</sup> which lends itself to multiple-objective and multiple-criteria possibilities such as need to be considered when dealing with the multi-faceted complexities that are likely to be involved in personnel planning. As a planning model, this one is designed to provide a choice among all possible alternatives in filling vacancies from within, from training, and from outside sources in accordance with stated goals.

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<sup>1</sup>Possible directions for such further research are presented in the body of the report and the model, and related developments, are carried to a point where the reasons for the suggested directions should be sufficiently clear.

<sup>2</sup>See [3] Appendix B and Chapter X for discussions of goal programming and related developments.

3.

These and other features of the model can best be exhibited, however, by proceeding toward a mathematical development such as will now be undertaken in the immediately following sections.

2. Development of the Constraints:

We shall normally be concerned with a sequence of periods, which can be indexed by  $t = 0, 1, 2, \dots$ , so that we can represent, say,

$$(1) \quad x_{ij}(t) = \text{number of personnel assigned to} \\ \text{"job type } i\text{" from "jth source" for} \\ \text{period } t.$$

The terms in quotation marks may be singled out for clarification by observing that different "job types" can refer to the same job classification when the latter requires further distinction by "claimant" or "activity." Similarly, "sources" can also be subdivided and identified with different indexes arranged according to geographic or other characteristics when desired.<sup>1</sup> Thus, to accommodate such distinctions we introduce the set of index'es defined by

$$J_{o\alpha} \equiv \{j: \text{from "outside source" } \alpha\}$$

(2.1) and

$$J_o \equiv \sum_{\alpha} J_{o\alpha}$$

For instance, we might associate blue collar sources with  $\alpha = 1, \dots, \alpha_1$  and white collar sources with  $\alpha = \alpha_1 + 1, \dots, \alpha_2$ . Similarly we might define more generally

$$(2.2) \quad J_{s\alpha} \equiv \{j: \text{from } s^{\text{th}} \text{ category of source } \alpha\}.$$

For instance  $s=0$ , as in (2.1) denotes "outside sources" while other values assigned to  $s$  might be associated with retraining or other such source possibilities.

<sup>1</sup>Cf., e.g., the distinction between "East Coast Welders" and "West Coast Welders" in the numerical illustration (below, section 5).

Now we introduce the following additional symbols and definitions,

$$(3) \quad c_i(t) = \text{salary for } i^{\text{th}} \text{ job type in period } t$$

$$f_k(t) = k^{\text{th}} \text{ manpower ceiling in period } t$$

$$I_k = \{\text{jobs } i \text{ under the } k^{\text{th}} \text{ manpower ceiling}\},$$

where we observe that  $I_k$  refers to the set of jobs, as indicated. Note that the  $c_i(t)$  and  $f_k(t)$  are prescribed values, as distinguished from the  $x_{ij}(t)$  which are to be chosen in order to optimize the planning objectives. Initially at least, these  $c_i(t)$  and  $f_k(t)$  values may be obtained by means of estimates or forecasts as well as from stipulated policies or regulations. However, the model to be erected will allow for evaluating the consequences of varying these  $f_k(t)$  and  $c_i(t)$  so that guidance for manpower planning may be secured from this quarter as well.

We can explicitly exhibit the relation between the  $x_{ij}(t)$  and  $f_k(t)$  by means of the following expression for the discrepancy between scheduled manpower attainments and the manpower ceilings,

$$(4) \quad \sum_{j \in I_k} x_{ij}(t) - f_k(t) \equiv E_k(t)$$

Clearly,  $E_k(t)$  may be positive, negative or zero. That is, we permit some violation of this  $f_k(t)$  ceiling--which we can control further, if desired, by prescribing further constraints on the permitted limits for these discrepancies.<sup>1</sup>

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<sup>1</sup>See, e.g., Appendix B and Chapter X in [3].

In the future we may also need some refinement of the variables  $x_{ij}(t)$  in order to designate their applicability to particular programs. Suppose, for instance, that program  $r$  in period  $t$  needs at least  $p_{ir}(t)$  men in job  $i$ . Then we shall need to write

$$(5) \quad x_{ij}(t) = \sum_r x_{ij}^r(t)$$

where  $x_{ij}^r(t)$  designates that part of  $x_{ij}(t)$  allocated to program  $r$ .

This manpower requirement for program  $r$  could then be written

$$(6) \quad \sum_j x_{ij}^r(t) \geq p_{ir}(t).$$

Similarly, we may require a  $b_r(t)$  to designate the dollar budget which is applicable to program  $r$  in period  $t$ . And we may need variables  $w_{ir}(t)$  to designate the chosen manpower reduction in job  $i$  of program  $r$ .

In this initial model we shall restrict ourselves to considerations of manpower planning in which our manpower sources are twofold: (1) from within the organization and (2) from outside sources.<sup>1</sup> Let us suppose that the changes and attrition from one job to another within the organization are given by the Markoff matrix  $M$  with element  $M_{il}$ , where  $M_{il}$  represents the proportion of those in job  $l$  in the previous period who will go to job  $i$  in the current period. In this Markoff representation, attrition or loss of manpower is represented by

$$(7) \quad \sum_i M_{il} < 1.$$


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<sup>1</sup>I.e., we do not treat retraining, etc., explicitly in this first model.

I.e., some of the persons in job  $i$  are not retained in any job  $i$ .

If

$$(8) \quad a_i = \text{number of persons in job } i \text{ initially (i.e., at } t=0)$$

then

$$(9) \quad \sum_l M_{il} a_l = \text{number of persons in job } i \text{ in period 1 from within}$$

The total in job  $i$  in period 1 is then given by

$$(10) \quad \sum_l M_{il} a_l + \sum_{j \in J_0} x_{ij}(1)$$

where, as before,  $J_0 = \{j: \text{from outside sources}\}$ . The number in job  $i$  in period 2 from within is given by

$$(11) \quad \sum_p M_{ip} (\sum_l M_{il} a_l + \sum_{j \in J_0} x_{pj}(1)).$$

At this point it is convenient to convert to matrix notation and so we introduce the following definitions:

$$(12) \quad x^j(t) = \begin{pmatrix} x_{1j}(t) \\ \vdots \\ x_{ij}(t) \\ \vdots \\ x_{nj}(t) \end{pmatrix} \quad a = \begin{pmatrix} a_1 \\ \vdots \\ a_i \\ \vdots \\ a_n \end{pmatrix}$$

$$(M)_i = (M_{i1}, \dots, M_{il}, \dots, M_{in}).$$

Hence, in matrix notation, the number in job  $i$  in period 2 from within is

$$(13) \quad (M^2)_i = a + \sum_{j \in J_0} (M)_i x_j^j(1)$$

and the total in period 2 is

$$(14) \quad (M^2)_i = a + \sum_{j \in J_0} (M)_i x_j^j(1) + \sum_{j \in J_0} x_{ij}(2).$$

Thus, in general, the total in job  $i$  in period  $t$  is

$$(15) \quad (M^t)_i = a + \sum_{\tau=1}^t \sum_{j \in J_0} (M^{t-\tau})_i x_j^j(\tau).$$

For this initial model we elect to stay within a total dollar budget that is stipulated for each period. Thus, if

$$(16) \quad B(t) = \text{total \$ budget for personnel in period } t,$$

then we shall require the  $x_{ij}(t)$  values to satisfy

$$(17) \quad \sum_i \sum_j c_i(t) x_{ij}(t) \leq B(t)$$

Note that  $j$  here runs over  $J_0$  and also another index which corresponds to the source "within the organization."

### 3. Representation of Model and Objectives

We shall here formulate an objective by supposing that we wish to minimize the discrepancies, as given in (4). I.e., we propose to minimize

$$(18) \quad \sum_k \sum_t \mu_{kt} |z_k(t)|,$$

where the  $\mu_{kt}$  are weights associated with the  $k^{\text{th}}$  manpower ceiling and the vertical strokes denote absolute values.

This nonlinear objective function may be reduced to more tractable form by utilizing the theory and procedures that we have developed in connection

with other personnel planning models.<sup>1</sup> Thus we introduce the new variables  $E_k^+(t)$ ,  $E_k^-(t) \geq 0$  and then represent

$$(19) \quad E_k(t) = E_k^+(t) - E_k^-(t).$$

The objective in (18) can then be represented by

$$\min \sum_k \sum_t u_{kt} (E_k^+(t) + E_k^-(t))$$

with

$$(20) \quad \sum_{i \in I_k} \sum_{\tau=1}^t \sum_{j \in J_0} (M^{t-\tau})_{ij} x_j^\tau(\tau) - E_k^+(t) + E_k^-(t) = g_k(t)$$

where

$$g_k(t) = f_k(t) - \sum_{i \in I_k} (M^t)_{ii} a.$$

In other words,  $g_k(t)$  is the net  $k^{\text{th}}$  manpower requirement which must be met, if at all, by outside recruitment.

In a similar manner, substituting for the  $x_{ij}(t)$ , the budget constraints become

$$(21) \quad \sum_i \sum_{\tau=1}^t \sum_{j \in J_0} c_i(t) (M^{t-\tau})_{ij} x_j^\tau(\tau) \leq B(t) - \sum_i c_i(t) (M^t)_{ii} a$$

$$\text{with } x_j^\tau(\tau) \geq 0$$

<sup>1</sup>Cf. the discussion in Chapter X of [3].

Thus the model may be represented

$$\sum_k \sum_t \mu_{kt} [E_k^+(t) + E_k^-(t)]$$

subject to

$$(22) \quad \begin{aligned} \sum_{i \in I_k} \sum_{\tau=1}^t \sum_{j \in J_0} (M^{t-\tau})_{ij} x_j(\tau) - E_k^+(t) + E_k^-(t) &= g_k(t) \\ \sum_{i} \sum_{\tau=1}^t \sum_{j \in J_0} c_i(t) (M^{t-\tau})_{ij} x_j(\tau) &\leq B(t) - c^T(t) M^t a \\ x_j(\tau) &\geq 0 \\ E_k^+(t), E_k^-(t) &\geq 0 \end{aligned}$$

where  $c^T(t) = (c_1(t), \dots, c_n(t))$ .

#### 4. Transformation and Reduction of the Model

The model could be calculated as represented above. We note, however, that it is possible to simplify it by making certain transformation of the variables since the basic variables  $x^j(t)$  only enter in certain combinations. Thus, let

$$(23) \quad \begin{aligned} \xi(\tau) &= \sum_{j \in J_0} x^j(\tau) \\ \eta(t) &= \sum_{\tau=1}^t M^{t-\tau} \xi(\tau) \end{aligned}$$

Then

$$(24) \quad \begin{aligned} \eta(t+1) &= \sum_{\tau=1}^{t+1} M^{t+1-\tau} \xi(\tau) \\ &= M \sum_{\tau=1}^t M^{t-\tau} \xi(\tau) + \xi(t+1) \\ &= M \eta(t) + \xi(t+1) \end{aligned}$$

Note that since  $\xi(t+1)$  are vectors of decision variables and are non-negative, we can replace them by the choice vectors  $\eta(t)$  with the requirement

$$(25) \quad \eta(t+1) - M \eta(t) \geq 0$$

and

$$\eta(t) \geq 0$$

The model can now be represented

$$\min \sum_k \sum_t \mu_{kt} [E_k^+(t) + E_k^-(t)]$$

subject to:

$$\sum_{i \in I_k} \eta_i(t) - E_k^+(t) + E_k^-(t) = g_k(t)$$

$$\sum_i c_i(t) \eta_i(t) \leq B(t) - c^T(t) x_a$$

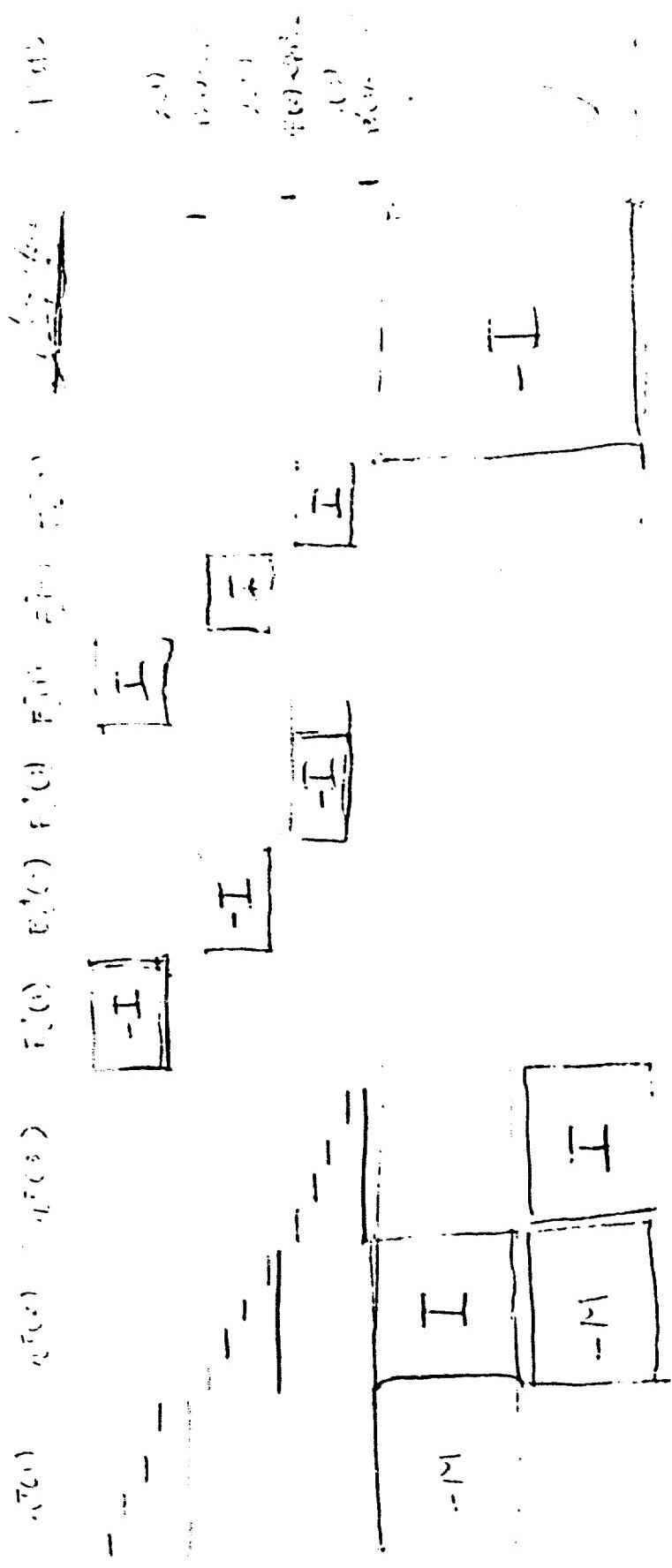
$$- (M) \eta_i(t) + \eta_i(t+1) \geq 0$$

$$\eta_i(t), E_k^+(t), E_k^-(t) \geq 0$$

where  $\eta_i(t)$  is the  $i^{\text{th}}$  component of  $\eta(t)$ .

Schematically, the non-zero coefficients may be arrayed as in Figure 1, below.

Figure 1



5. Numerical Illustration:

In order to make the preceding developments somewhat more concrete, we now proceed to a numerical illustration. This is the only purpose of the illustration, however, since the data are all purely hypothetical and contrived for a highly simplified two-period categorization. To emphasize this even further, we refrain from pushing on to a solution of the resulting model since this would be of no interest per se. Instead, we shall discuss some of the computation possibilities as well as the evaluation and other possibilities for an integrated personnel planning system--<sup>as</sup> these might be attended to by further research.

For illustrative job types we shall utilize the following:

<u>i</u>	<u>Description</u>	<u>Abbreviation</u>
1	Personnel Analyst	PA
2	Mechanical Engineer	ME
3	Welder -- West Coast	WC
4	Welder -- East Coast	EC

The transition probabilities and the related Markoff matrix, M, which we shall use in this illustration is arranged so that the transitions<sup>1</sup> are from  $\ell$  to i. Using blank cells to represent  $M_{i\ell} = 0$ , we suppose M to be

$\ell$	PA 1	ME 2	WC 3	EC 4
i	PA 1	ME 2	WC 3	EC 4
PA 1	.8	.1		
ME 2	.1	.7		
WC 3			.6	
EC 4			.1	.9

---

<sup>1</sup>I.e., the  $M_{i\ell}$  represent the transition rates from  $\ell$  to i in each cell of M.

Restricting our illustration to only two periods, we represent the  $g_k(t)$  values by<sup>1</sup>

$t$	$k$	1	2	3	4
1		30	200	600	500
2		70	300	450	500

Next, we hypothesize some representative salary values in which we suppose that  $c_1(1) = c_1(2)$  for all  $i$ . Stating these hypothesized values in units of \$1,000 we have

$c_1$	$c_2$	$c_3$	$c_4$
15	13	8	7

Stipulated budget ceilings are also stated in units of \$1,000 for each period as

B (1)	B (2)
12,000	13,000

for

Initial  $a_i$  values as components/the vector  $a$  of personnel already in position at the start are

PA	ME	WC	WE
25	220	550	450

---

<sup>1</sup>If wanted the  $f_k(t)$  values may be obtained from

$$f_k(1) = g_k(1) + (M)_k a$$

$$f_k(2) = g_k(2) + (M^2)_k a$$

Thus to obtain the value for  $c^T(1) M a$  and  $c^T(2) M^2 a$  we obtain

$$c^T M = (13.3, 10.6, 5.5, 6.3)$$

which can be multiplied by the corresponding components of  $a$ , and summed, to yield

$$c^T(1) M a = c^T M A = 8525$$

and by a similar route we obtain

$$c^T(2) M^2 a = c^T M^2 A = 6940$$

Referring back to the data for dollar budget ceilings we thus obtain

$$B(1) - c^T M a = 12,000 - 8,525 = \$3,475$$

$$B(2) - c^T M^2 a = 13,000 - 6,940 = \$6,060.$$

Positioning these data in the form suggested by Figure 1, we obtain the concrete representation that is depicted in Figure 2.

## Figure

It may be noted from the above figure that a method of "model approximation" may be used which is analogous to the one developed for the pipeliner example in association with the oil field development programming undertaken by ARAMCO.<sup>1</sup> Thus, in Figure 1, if the first sets of unknowns ( $\eta^T(1)$  then  $\eta^T(2)$ ) had values substituted for them, then these sets of equations would reduce to individual lower-bound inequalities on  $\eta^T(2)$  and  $\eta^T(3)$ . The resulting structure by changes of scale and variables and multiplication of equations by suitable constants would be reduced to a very special form of the distribution (or transportation) model which could be immediately brought into contact with the highly efficient algorithms that are available for these classes of models.<sup>2</sup> The same type of parametric procedure as in the pipeliner model could then be used to obtain an optimal exact solution.

Before work of the above type is undertaken, however, it is prudent to consider ways in which the model might itself be altered or extended. Training facilities and environmental factors have already been noted as candidates for explicit treatment and this does not exhaust the list. A strategy for staging such further developments might thus also form a part of the topics to be considered after the model presented above is reviewed in the context of the 3-pronged OCMM program which was discussed at the outset of this report.

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<sup>1</sup> See e.g., Chapter XVI in [ ].

<sup>2</sup> Cf., e.g., Chapter II and XIV in [ ].

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34.1 Memo to Files from A. Charnes and W. W. Cooper  
  
(a) Memo of June 15, 1967 covering minutes of a conference with Mr. Robert Willey, Captain P. A. Gisvold, Mr. R. H. Rawdon, Mr. W. N. Price and Lt. R. J. Niehaus.  
  
(b) Memo of October 13, 1967, covering review of proposed model with Mr. Robert Willey, Captain P. A. Gisvold, Mr. P. Meyerson, Mr. R. H. Rawdon, Lt. R. J. Niehaus, Mr. W. Price and Mr. J. Treires. Note, this includes Memo of 10 October 1967 prepared by Lt. R. J. Niehaus and revised in association with A. Charnes and W. W. Cooper covering (i) June 15, 1967 meeting with Mr. Willey (ii) development of a Markov model program and (iii) description of this plus the model developed in the meeting of Niehaus, Charnes and Cooper in Pittsburgh on 2 August 1967 as well as (iv) description of this and other research under way at that time.

- (c) Memo of December 4, 1967 covering meeting of Lts. Lts. R. J. Niehaus and David Sholtz with Professors A. Charnes and W. W. Cooper in Pittsburgh on 12/4 - 12/5/67. Rough notes only, to cover redo of model in notes of 8/2/67.
- (d) Memo of August 2, 1967 covering meeting of Lt. R. J. Niehaus and Professors A. Charnes and W. W. Cooper. Rough notes only, to record model details during meetings of 8/1- 8/2/67.
- (e) Memo of 29 June 1967 covering meeting with W. N. Price, R. H. Rawdon, R. J. Niehaus and P. Weinstein. Review of relation between concept and systems work and modelling research. See also memo of 7 July 1967 prepared by R. J. Niehaus.
- (f) Memo of 16 May 1967 covering results of field trip to Portsmouth Shipyard on May 7, 8, 9, 1967 and discussions with Admiral Hushing and Donald Holster (and others) on WOWANS scheduling by Lt. Niehaus in association with Professors A. Charnes and W. W. Cooper.
- (g) Memo of 3 March, 1967 covering meetings of Washington on 2/27-2/28/67 with Niehaus, Rawdon, Meyerson, Langley and others on Model objectives and strategy for obtaining necessary field background and experience. See also memo of 28 March 1967 by Lt. Niehaus.

#### 34.2. James J. Treires

- (a) Memo of 1 November 1967 "Comments on Memorandum on Manpower Planning Models Assumptions"
- (b) Memo of October 1967 "Forecasting the Navy's Civilian Manpower Requirements: Problems and Possibilities"

#### 34.3. Paul A. Weinstein

- (a) Memo of 5 May 1967, "A Suggested Research Program of Manpower Projections for Office of Civilian Manpower Management, U. S. Navy"
- (b) Memo of 15 August 1967 "Manpower Projections for the Civilian Workforce"

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